Improving the Accuracy of Structural Fatigue Life Tracking Through Dynamic Strain Sensor Calibration

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ABSTRACT

The ability to accurately determine the amount of structural life that has been consumed in military aircraft can be compromised by the inability to be consistent in the manufacture and installation of strain sensors and general aircraft-to-aircraft variations in the structures themselves. The variations must be accounted for in order to be able to make correct decisions - regarding the ability to safely operate the aircraft as well as reducing the need to purchase new aircraft (resulting from retiring of aircraft with remaining useful life) - which are based on fatigue life calculations. Accurate strain gauge calibration is thus necessary to ensure accurate aircraft fatigue usage estimates. However, the methods that are currently used for strain gauge calibration are costly, time consuming, or inaccurate.

To address these issues, the authors are developing an innovative strain sensor calibration system that uses a portable device to 1) apply a low level and localized dynamic load near the strain gauge, 2) record the input load and structural response measured by the strain gauge, 3) evaluate the measurements relative to a reference structure, and 4) provide a calibration factor for each individual strain sensor/structure. This paper presents an overview of the approach and describes experimental results for both baseline (static) and dynamic excitation tests. The accuracy goal of 1% has been set for the calculated calibration factors on simpler structures and 2% on trial parts of increasing complexity. Tests were thus conducted to verify test repeatability and evaluate calibration accuracy in these scenarios.

INTRODUCTION

Decisions regarding the ability to safely operate military aircraft are currently performed with the aid of structural fatigue life tracking estimates that are based on the load history (cyclic and peak loads) and 'structural life consumption' models for individual aircraft. The load history going into these models is determined using in-flight strain sensor data. However, the usefulness of the strain data can be

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14. ABSTRACT
The ability to accurately determine the amount of structural life that has been consumed in military aircraft can be compromised by the inability to be consistent in the manufacture and installation of strain sensors and general aircraft-to-aircraft variations in the structures themselves. The variations must be accounted for in order to be able to make correct decisions - regarding the ability to safely operate the aircraft as well as reducing the need to purchase new aircraft (resulting from retiring of aircraft with remaining useful life) - which are based on fatigue life calculations. Accurate strain gauge calibration is thus necessary to ensure accurate aircraft fatigue usage estimates. However, the methods that are currently used for strain gauge calibration are costly, time consuming, or inaccurate. To address these issues, the authors are developing an innovative strain sensor calibration system that uses a portable device to 1) apply a low level and localized dynamic load near the strain gauge, 2) record the input load and structural response measured by the strain gauge, 3) evaluate the measurements relative to a reference structure, and 4) provide a calibration factor for each individual strain sensor/structure. This paper presents an overview of the approach and describes experimental results for both baseline (static) and dynamic excitation tests. The accuracy goal of 1% has been set for the calculated calibration factors on simpler structures and 2% on trial parts of increasing complexity. Tests were thus conducted to verify test repeatability and evaluate calibration accuracy in these scenarios.

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compromised by the inability to consistently manufacture and install the sensors as well as by aircraft-to-aircraft variations in the structures themselves. As such, variations in strain readings in different aircraft can be greater than 10% under the same loading conditions [1]. These differences must be accounted for to have acceptable accuracy levels in the ultimate life usage calculations.

Unfortunately, current strain sensor calibration methods are inadequate, expensive, and time consuming. For example, the ideal calibration approach involves placing the entire aircraft in a full scale test rig and applying known loads to the structure. This approach is extremely expensive and time-consuming, and thus cannot realistically be performed for every aircraft. Alternately, the aircraft could be flown in tightly prescribed maneuvers where loads can be fairly well determined. However, this approach is far less accurate, and in some cases, it is difficult to prescribe appropriate maneuvers to repeatedly test (load) certain sections within the aircraft. As such, a need exists for a cost/time-effective means to calibrate strain gauges on each aircraft with an accuracy that is comparable to the full scale test rig approach.

In order to address this need, the authors are developing an innovative strain sensor calibration method (Figure 1) that utilizes a hand-held device to introduce low amplitude excitations near the target strain gauge to create localized dynamic loads that are measurable by the gauge but don't sacrifice the structural integrity of the aircraft part [2]. The resulting structural response is then compared with the input force (measured using an integrated force sensor) to calculate correlation metrics using advanced signal processing methods. A calibration factor is then generated for each strain sensor by comparing the calculated correlation metrics to those from a reference aircraft (or sufficient model). This novel approach should allow fleet aircraft strain calibration to be achieved with full-scale test accuracy without the cost and complexity of a full-scale test. Once fielded, the system will produce a reliable and easy-to-use strain gauge calibration method that can be used on each individual aircraft. This will result in a more accurate determination of aircraft service life.

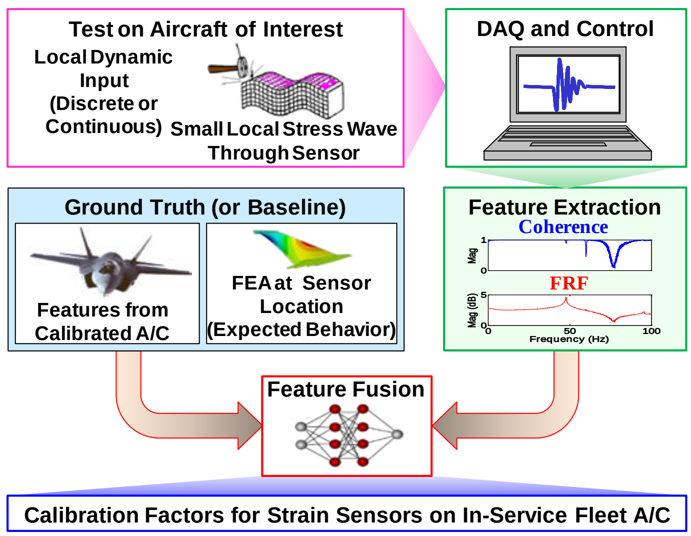


Figure 1 – Strain Sensor Calibration Concept

DYNAMIC CALIBRATION METHOD OVERVIEW

The key steps in the developed strain gauge calibration process (Figure 2) include: 1) exciting the fleet aircraft structure using a periodic or impact force; 2) measuring the force input and response (using a force sensor and the strain gauge respectively); 3) performing sensor and signal integrity checks to flag hardware degradation or poor excitations/data; 4) applying signal preprocessing techniques such as filtering, noise reduction, and outlier detection/removal; 5) extracting calibration features from the force and strain signals (using signal processing techniques in the time and frequency domains); 6) calculating calibration factors by correlating the features with ones determined from a reference aircraft structure using the same measurement process; and 7) fusing the calculated factors to obtain a final calibration factor of the strain sensor. As seen in the figure, two different methods of exciting the structure are being evaluated. These are 1) an impact force input (using an impact hammer) and 2) a periodic impact (using a shaker) method. Although both are being evaluated, the best performing and implementable approach will ultimately be selected for at-wing application. The results from applying this calibration process on structures of increasing complexity are described in this paper.

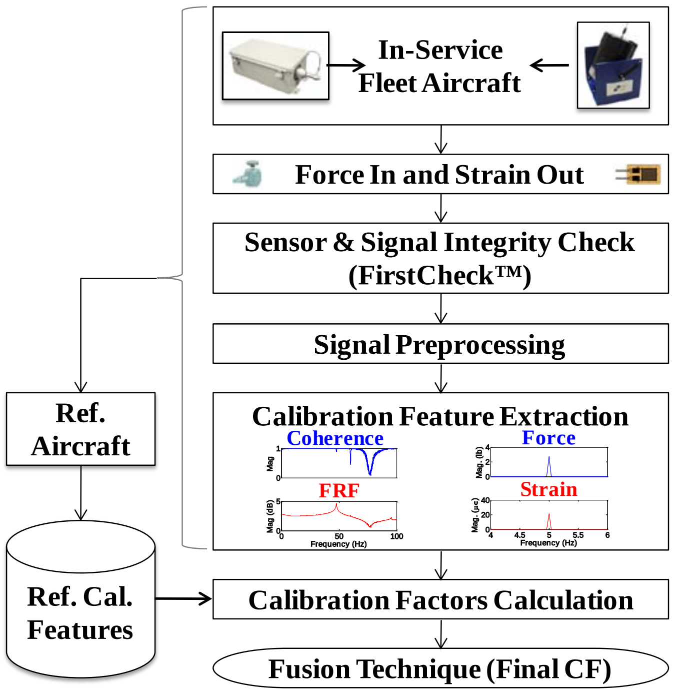
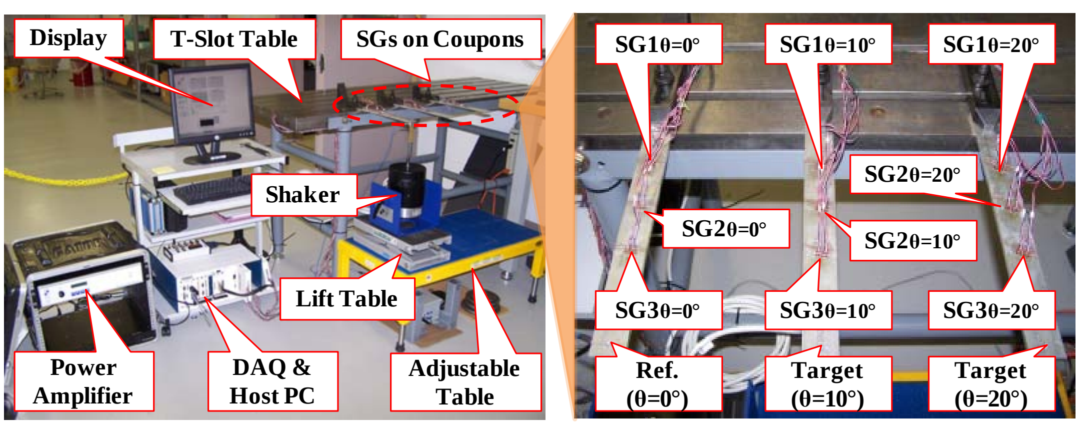


Figure 2 – Strain Sensor Calibration Process

APPLICATION TO CANTILEVERED BEAMS – "SIMPLE STRUCTURE"

In order to validate the basic dynamic strain sensor calibration concept, the authors first performed tests on a simple cantilevered beam structure (Figure 3). The experimental set-up included: three identical 6061-T6511 aluminum coupons (12"(L) x 1.5"(W) x 0.375"(D)) that were mounted to a heavy T-slot table; two excitation devices [an electrodynamic modal shaker (TMS 2100E11) and an electric impact hammer (TMS 086M92ES)]; an integrated force sensor (PCB 208C03); LabVIEW-based data acquisition & control software; MATLAB-based analysis software; and six dual-element strain gauges (Vishay N2A-13-S061P-350) per coupon.



(a) Experimental Setup (b) Strain Gage Location and Alignment Angle

Figure 3 – Experimental Setup with Aluminum Coupons

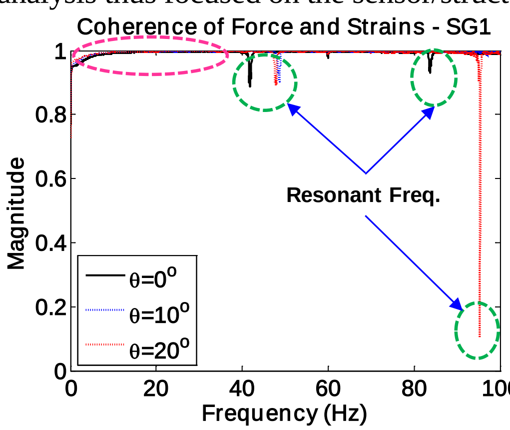
On each coupon, three gauges were mounted on the top surface and three were mounted on the bottom surface (in full-bridge configuration), located at 4", 6.5", and 9" from the loading point. On each coupon, the gauges were installed with different alignment angles with respect to the principal axis at each location (Figure 3b). This was done to evaluate the effects of inconsistent sensor installation, which as previously mentioned, is a potential issue in the field. The three coupons were tightly clamped along the side of the T-slot table in the cantilevered configuration shown in Figure 3. A hole, located close to the free end of each cantilevered coupon, served as the loading point for static weight or dynamic excitation. The coupon with strain gauges at 0° alignment angle (far left in the figure) was used as the 'reference'. The other two coupons (in which the strain gauges were misaligned at 10° and 20° angles) were used as the 'target' structures (simulating a poorly installed sensor).

Baseline Data Collection: As an initial step, a series of static load tests were performed on the aluminum cantilever coupons to determine the actual calibration factors for each strain gauge. This test mimics the 'ideal' calibration process and provides a benchmark that is used to assess the accuracy of the approach. Weights from 2.5 to 15lb (in 2.5lb increments) were hung from the structure, and the resulting strain signals were measured. The relationship between the static load and resulting strain was then determined using a linear function. This was used to determine the baseline calibration factor (CF) for each gauge (Table 1).

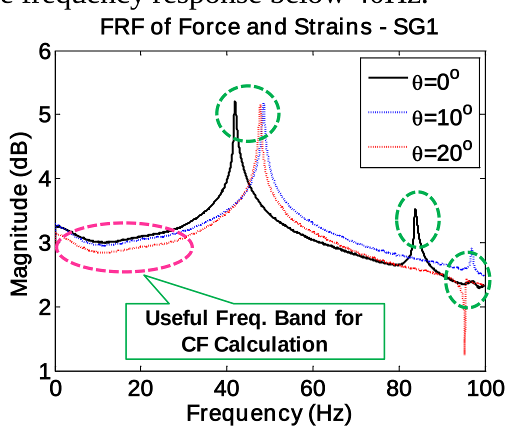
Table 1 – Baseline CFs on Ref SGs at ($SG1_{\theta=0°}$, $SG2_{\theta=0°}$, and $SG3_{\theta=0°}$, refer to Figure 3b) at Nominally Same Location but with Different Alignment Angle

SG and Loading Distance	SG1 (L=9")		SG2 (L=6.5")		SG3 (L=4")	
Alignment Angle	θ=10°	θ=20°	θ=10°	θ=20°	θ=10°	θ=20°
Baseline CF	1.041	1.183	1.041	1.183	1.042	1.183

Impact Excitation Method: Next, a series of impact excitation tests were performed on the reference coupon and two target cantilever coupons using the electric impact hammer. Figure 4 shows an example of the coherence and Frequency Response Function (FRF) results from these tests. As seen, the structural resonant frequencies occurred at ~40Hz and 80Hz for the reference coupon and ~50Hz and 90Hz for the target coupons. At those frequencies, the coherence and FRF values significantly drop and increase respectively. To minimize the effect of uncertainty at resonance, the analysis thus focused on the sensor/structure frequency response below 40Hz.



(a) Coherence



(b) FRF

Figure 4 – Coherence and FRF of Force and Strain

As seen in the results table (Table 2), the impact CF satisfied the criterion of less than 1% calibration error for the simple structure (with one exception).

Table 2 – Impact CFs on Ref SGs at (SG1$_{\theta=0°}$, SG2$_{\theta=0°}$, and SG3$_{\theta=0°}$) at Nominally Same Location but with Different Alignment Angle

SG and Loading Distance	SG1 (L=9")		SG2 (L=6.5")		SG3 (L=4")	
Alignment Angle	θ=10°	θ=20°	θ=10°	θ=20°	θ=10°	θ=20°
Baseline CF	1.041	1.183	1.041	1.183	1.042	1.183
Impact CF	1.043	1.180	1.042	1.169	1.040	1.179
CF Deviation (%)	0.2	-0.3	0.1	-1.2	-0.2	-0.3
Average Result	0.4% [Using absolute values of CFs]; 0.2% [without outliers]					

Periodic Excitation Method: A series of periodic tests were then performed on the coupons at excitation frequencies ranging from 1-10Hz (in 1 Hz increments). The spectra of the signals were calculated and used to extract the excitation frequency components. The strain readings were then normalized by the force measurement to compensate for variations in input force. The results can be seen in Table 3. As seen, the periodic CF satisfied the less than 1% criterion for all test cases.

Table 3 – Periodic CFs on Ref SGs at (SG1$_{\theta=0°}$, SG2$_{\theta=0°}$, and SG3$_{\theta=0°}$) at Nominally Same Location but with Different Alignment Angle

SG and Loading Distance	SG1 (L=9")		SG2 (L=6.5")		SG3 (L=4")	
Alignment Angle	θ=10°	θ=20°	θ=10°	θ=20°	θ=10°	θ=20°
Baseline CF	1.041	1.183	1.041	1.183	1.042	1.183
Periodic CF	1.049	1.188	1.047	1.173	1.042	1.188
CF Deviation (%)	0.8	0.4	0.6	-0.8	0	0.4
Average Result	0.5% [Absolute values]					

APPLICATION TO REPRESENTATIVE AIRCRAFT STRUCTURE

After validating the approach on the simple structures described above, a more complex part was constructed to validate the approach for a representative structure. The structure represented a simplified version of an aircraft wing structure (Figure 5). It consisted of 20+ metallic parts of high-strength corrosion resistant 7075-T6 alloy, and included hinge lugs, a bulkhead, spars, and wing skins that were fastened together using welds, rivets, and screws. The overall size of this test wing was 24" wide, 22" long and 9" high. The specimen was mounted on a T-slot table through a mounting fixture with a sliding slot. This test specimen was designed to enable evaluation of the transmissibility of the excitations through complex paths that are representative of those seen in the field.

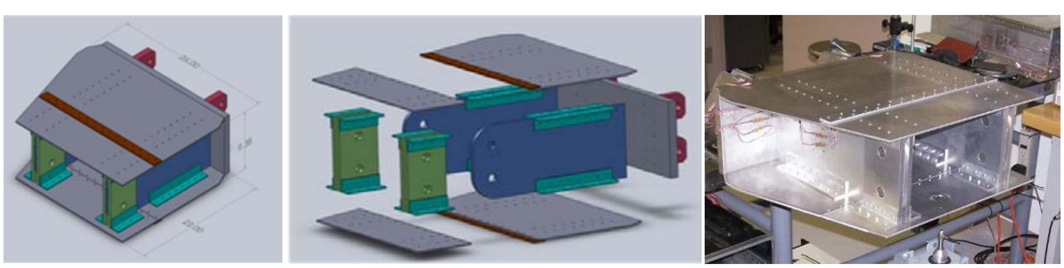


Figure 5 – Representative Aircraft Structure

Figure 6 shows the strain sensor locations and alignment angles that were used. Half bridge tee rosette-type strain gauges (Vishay C2A-13-125LT-350) were placed on the left top lug with alignment angles of 0° and 10. Full bridge shear pattern-type strain gauges (Vishay CEA-13-187UV-350) were placed on the bulkhead and spars with alignment angles of 0°, 10°, and 20°. Similar to before, the strain gauges with alignment angles of 0° were used as the reference for CF calculation.

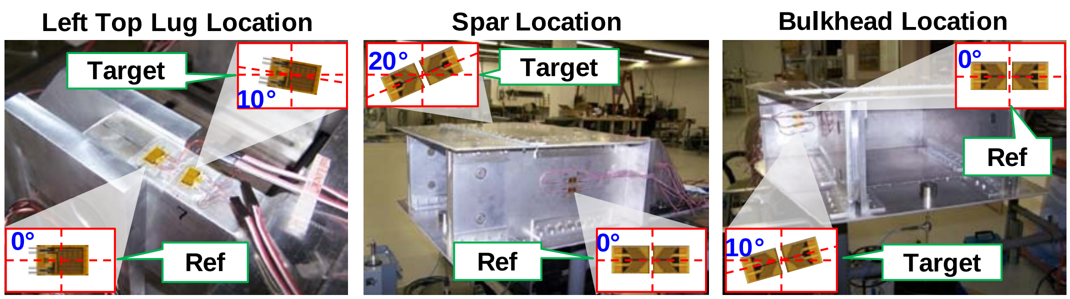


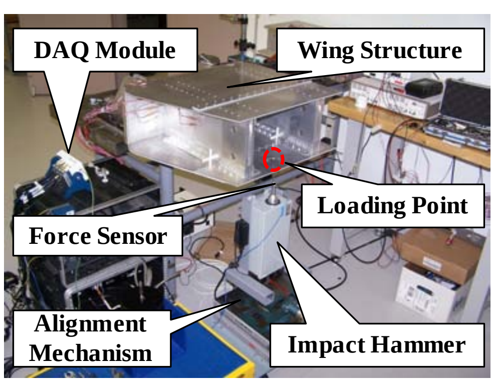
Figure 6 – Wing Structure Sensor Locations (with Alignment Angle)

Baseline Data Collection: Similar to the test procedure used for the cantilevered beam tests, static tests using weights ranging from 25-195lb were used to determine the actual calibration factors. Table 4 summarizes the baseline CFs of each pair of strain gauges. In the table, the distance represents the *Euclidean distance* between the loading point and sensor location. The actual transmission paths were longer and more complicated.

Table 4 – Baseline (or Static) CFs on Wing Structure

Location	Left Top Lug		Spar		Bulkhead	
Gauge	Ref	Target	Ref	Target	Ref	Target
Distance	28.0"	26.5"	12.7"	12.5"	20.8"	20.6"
Angle	θ=0°	θ=10°	θ=0°	θ=20°	θ=0°	θ=10°
Baseline CF	0.362		0.728		1.050	

Impact Excitation Method: Figure 7 (left) shows the test set-up for the impact tests. As seen, the loading point was again positioned at the free end of the structure. The de-noised signals were then used to calculate the coherence and frequency response function (right side of Figure 7). In this case, the frequency band of 2-50Hz was chosen for CF calculation.



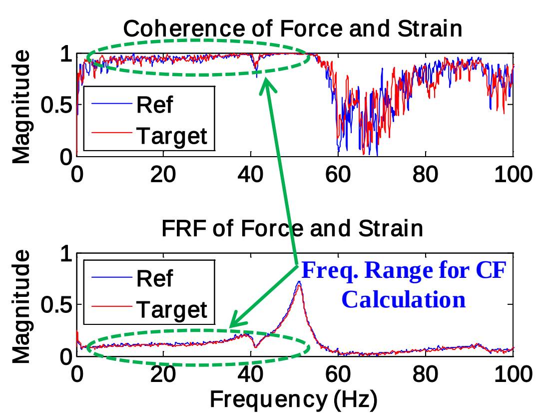


Figure 7 – Impact Test Setup (left) and Resulting Coherence and FRF (right)

Table 5 summarizes the impact CFs of each pair of strain gauges and their deviations from the baseline CFs. As seen, <1.5% error was achieved in all locations. This is quite impressive when considering the loading distance and complexity of the transmission paths. It is also worth noting that spar sensors were actually located on different sides of the structure, the reference was on the right spar and the target was on the left spar. In addition, the target gauges were offset by 1" (in addition to being misaligned) with respect to the reference gauge. As such, these test conditions represented a case with *very poor* sensor installation and are thus encouraging. These results are expected to improve by impacting the structure at locations that are far closer to the gauge. This will be evaluated in future work.

Table 5 – Impact CF on Wing Structure

Location	Left Top Lug		Spar		Bulkhead	
Gauge	Ref	Target	Ref	Target	Ref	Target
Distance	28.0"	26.5"	12.7"	12.5"	20.8"	20.6"
Angle	θ=0°	θ=10°	θ=0°	θ=20°	θ=0°	θ=10°
Baseline CF	0.362		0.728		1.050	
CF	0.367		0.720		1.046	
Dev (%)	1.4		-1.1		-0.4	

Periodic Excitation Method: A series of periodic tests (Figure 8), were then performed at excitation frequencies of 2-50Hz. Depending on the excitation frequency, a range of 1-5lbs force was applied to the wing structure. The CFs of each pair of strain gauges was then calculated using the same process used in the beam application. Once again, impressive results (Table 6) were produced at the Top Lug and Bulkhead locations, when considering the loading distance, transmission paths, and sensor offset/misalignments. Unfortunately, the bridge terminal on the target spar location was broken during these tests and the CF could therefore not be calculated.

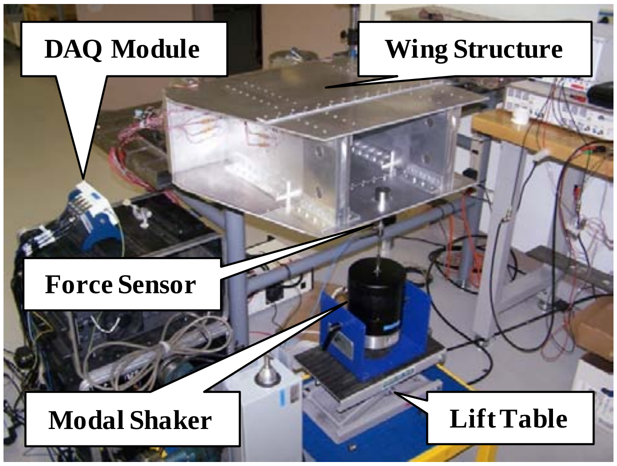


Figure 8 – Periodic Test Setup

Table 6 – Periodic CF on Wing Structure

Location	Left Top Lug		Spar		Bulkhead	
Gauge	Ref	Target	Ref	Target	Ref	Target
Distance	28.0"	26.5"	12.7"	12.5"	20.8"	20.6"
Angle	θ=0°	θ=10°	θ=0°	θ=20°	θ=0°	θ=10°
Static CF	0.362		0.728		1.050	
CF	0.360		N/A		1.0496	
Dev (%)	-0.6		N/A		-0.038	

CONCLUSIONS

To address the limitations (i.e., cost, time, accuracy, etc.) of current in-situ strain gauge approaches, the authors have developed novel dynamic strain sensor calibration methods that are based on periodic and impact excitations. The authors' approach applies low level, localized dynamic loads near the strain gauge (e.g., from a hand portable unit that produces vibrations) to obtain in-situ response information from individual gauges. This response information is merged with previous "ground truth" information to obtain calibrations for individual strain sensors on fleet aircraft. As described in this paper, verification tests have been performed on simple (cantilevered beams) and more complex (a wing structure) to evaluate the accuracy of the approach. Even after simulating inconsistent sensor installations (by rotating sensors on the target structure by 10° and 20° and offsetting them by a slight distance) and loading the structure at considerable distances, the experimental results showed that the dynamic strain sensor calibration methods can accomplish calibration accuracy to the desired level of less than 1% error on the simpler structure and less 2% error on the more complex structure.

As a next step, a rugged, hand-held, easy-to-use device is being designed to allow implementation of the approach in the field. The device will enable a maintainer to quickly, cost-effectively, and accurately calibrate strain gauges at multiple sensor locations on an aircraft. This capability will enable more frequent and accurate strain gauge calibration, which will help to ensure aircraft fatigue usage estimates are based on reliable structural load histories. This will reduce the cost associated with purchasing new aircraft (resulting from the retiring of aircraft with remaining useful life), and more importantly, reduce the risk associated with flying unsafe aircraft. The work described in this paper will thus have a positive effect on legacy structural lifing programs, such as the Navy's Structural Assessment of Fatigue Effects (SAFE) initiative, and emerging structural prognostics and health management (SPHM) technologies that are being developed for platforms such as the Joint Strike Fighter [3]. The big picture goal of all this work is to increase fleet availability and reduce costs (O&M and procurement).

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